World Academy of Science, Engineering and Technology
International Journal of Health and Medical Engineering
Vol:6, No:11, 2012

The Effect of Natural Light on the Performance of Visible Light Communication Systems

Mahmoud Beshr, Ivan Andonovic, and Moustafa H.Aly

***Abstract*—**Visible Light Communication (VLC) offers advantages of low energy consumption, licence free and RF interference free operation. One application area for VLC is in the provision of health centred services circumventing issues of interference with any biomedical device within the environment. VLC performamce is affected by natural light restricting systems avilability and relibility. The paper presents an analysis of the performance of VLC systems under different meteorological conditions. The evaluation considered the impact of natural light as a function of different reflection surfaces in different room sizes.

***Keywords*—**Impulse reponse, Visible light communication, Natural light, Performance analysis.

I. INTRODUCTION

CONCERNS about energy consumption are leading to the phasing out of incandescent sources stimulating rapid growth in the use and development of solid-state sources [4], [6]. Visible Light Communication (VLC) overlays harness these light emitting diodes (LEDs) for communication purposes at the same time. VLC has the potential to provide high data rate, low energy consumption, license free and interference less operation especially in environments where issues with RF interference are a fundamental barrier.

VLC systems are affected by natural light (weather conditions). The performance of VLC systems has been evaluated but without rigorous consideration of the impairments owing to natural light [1], [2], [4]. In previous research, natural light has been treated as Gaussian noise; this research takes into consideration the variation of natural light intensity over the year under different metrological conditions. Moreover the VLC impulse response has to date been determined solely for single reflection for standard room sizes [1], [4].

Here an evaluation of the impulse response for different room sizes for both line-of-sight (LOS) and non-line of sight (NLOS) components up to the fifth reflection is presented.

The paper is organized as follows. Section I presents the VLC system architecture and its mathematical representation Section II presents the impulse response of the system for LOS and NLOS components, Section III summarizes the foundation to treating natural light and simulation conditions. Section IV presents VLC system performance considering natural light. Section V contains the conclusions.

Mahmoud Beshr is with Strathckyde University, Electrical and Electronic Engineering Department, Glasgow, UK.
Ivan Andonovic is with Strathckyde University, Electrical and Electronic Engineering Department, Glasgow, UK.
Moustafa H. Aly is with Arab Academy for Science and Technology, Electronics and Communication Engineering Department, Alexandria, Egypt.

II. SYSTEM MODEL

It is assumed that the optical path is subject to multiple refections [2] (Fig. 1). It is also assumed that the transmitter is positioned on the ceiling of the room with the receiver on the floor. The tranmitter radiated light is characterised by Φ_1, equal to the viewing angle of the LED. The beam is incident with angle θ_1 after distance *d* from source to reflection point.

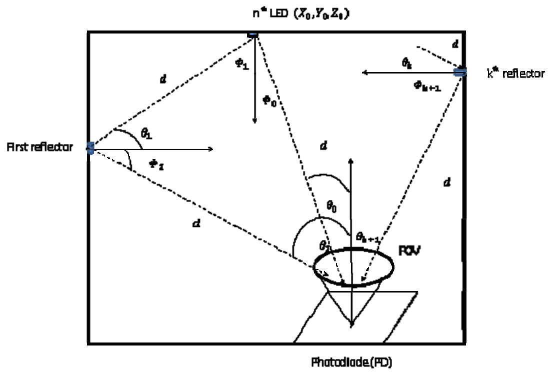

Fig. 1 Geometry of the analysis environment comprising n transmitter LEDs and a receiver photodiode (PD)

The link geometry shown in Fig. 1 is considered in order to calculate the impulse response for the case of multiple reflections and multiple sources. The impulse response is given by Equation (1), where N_{LED} is the total number of LEDs. It was assumed that each LED in the transmitter emits equal power. The response after k-bounces of the n Th LED source is [2], [3], and [7]:

$$h(t) = \sum_{n=1}^{N_{LED}} \sum_{k=0}^{\infty} h^{(k)}(t; \Phi_n) \quad (1)$$

$$h^{(k)}(t; \Phi_n) = \int_s \left[L_1 L_2 \ldots\ldots L_{K+1} \Gamma_n{}^{(k)} rect\left(\frac{\theta_{k+1}}{FOV}\right) \times \delta\left(t - \frac{d_1 + d_2 + \cdots d_{k+1}}{c}\right) \right] d\, A_{ef},\ k \geq 1 \quad (2)$$

where

$$L_1 = \frac{A_{ref}(m+1) cos^m \Phi_1 cos\theta_1}{2\pi {d_1}^2}$$

$$L_2 = \frac{A_{ref}\cos\Phi_2 cos\theta_2}{\pi {d_2}^2}$$

$$L_{k+1} = \frac{A_{PD}\cos\Phi_{k+1}\cos\theta_{k+1}}{\pi {d_{k+1}}^2}$$

L_{k+1} is the pass loss for each reflection, the directivity of the light beam is controlled by the mode number of radiation, $m = -1/\log 2(\cos\phi_{1/2})$ and it is governed by the LED viewing angle ($2\phi_{1/2}$). It is noted that the more distance (dk) between transmitter and receiver the less power received. θk and ϕk are the angles of incidence and irradiance respectively. The field of view is the critical design parameter photodiode can only detects light beam with angle less than FOV. Hence it is considered as acceptance angle.The rectangular function rect (x) is given by [2], [5].

$$rect(x) = \begin{Bmatrix} 1 & for\ |x| \le 1 \\ 0 & for\ |x| > 1 \end{Bmatrix} \quad (3)$$

The constant term, c is the speed of light.

Let ${\Gamma_n}^{(k)}$in Equation (2) denotes the power of the reflected ray after k- bounces from the n^{th} LED. The reflected power can be calculated as:

$${\Gamma_n}^{(k)} = \int_\lambda \Phi_n(\lambda)\,\rho_1(\lambda)\rho_2(\lambda)\ldots\ldots\rho_k(\lambda)d\lambda \quad (4)$$

The reduced form of Equation (4) with lower accuracy is described by:

$$\bar{\Gamma}_n^{(k)} = P_n\bar{\rho}_{n,1}\bar{\rho}_{n,2}\ldots\ldots\ldots\ldots\bar{\rho}_{n,k} \quad (5)$$

where $\bar{\rho}_{n,k} = \frac{1}{P_n}\int_\lambda \Phi_n(\lambda)\rho_k(\lambda)d\lambda$ is the average reflectance, and $P_n = \int_\lambda \Phi_n(\lambda)d\lambda$ is the radiant power from the n^{th} LED source for k=1. Equations (4) and Equation (5) have the same value [2]:

$${\Gamma_n}^{(1)} = \bar{\Gamma}_n^{(1)} = \int_\lambda \Phi_n(\lambda)\rho_1(\lambda)d\lambda \quad (6)$$

However, the differences are more obvious for the case of higher order reflections; the photodiode position for LOS is given as [2], [7]:

$$h^{(0)}(t;\Phi_n) = L_O P_n rect(\frac{\theta_o}{FOV})\delta(t - \frac{d_o}{c}) \quad (7)$$

where

$$L_O = \frac{A_{PD}(m+1)cos^m\Phi_o cos\theta_o}{2\pi {d_0}^2}$$

A. Signal to Noise Ratio (SNR)

In order to compute the SNR and concomitant Bit Error Rate (BER), it was assumed that the transmitter sends data at a bit rate R_b using ON-OFF keying (OOK) with NRZ pulses. The transmitted average power is P_t, the received average power is $p = H(0)P_t$, where the channel DC gain is determined as detailed in the previous section. The channel is assumed to be distortion free with gain H (f) = H (0) for all frequencies. The receiver pre-amplifier is followed by an equalizer. Each sample of the equalizer output contains noise with a total variance given by [2], [3], [7], [8]:

$${\sigma_{total}}^2 = {\sigma_{shot}}^2 + {\sigma_{thermal}}^2 \quad (8)$$

The shot noise is;

$${\sigma_{shot}}^2 = 2qRp_nI_2R_b \quad (9)$$

while the thermal noise variance is given by:

$${\sigma_{thermal}}^2 = \frac{4KT}{R_F}I_2R_b + \frac{16\pi^2KT}{g_m}\left(\Gamma + \frac{1}{g_mR_D}\right){C_T}^2I_3{R_B}^3 + \frac{4\pi^2K{I_D}^aC_T{}^2}{{g_m}^2}I_f{R_b}^2 \quad (10)$$

The SNR is expressed using Equation (8), Equation (9), Equation (10);

$$SNR = \frac{(RP)^2}{{\sigma_{total}}^2} \quad (11)$$

and the BER is given by;

$$BER = Q(\sqrt{SNR}) \quad (12)$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-y^2/2}dy \quad (13)$$

III. System Impulse Response

TABEL I
LIGHT REFLECTION FOR SINGLE SOURCE IN 15M*15M*3M ROOM SIZE

	Plaster Wall (W)	Floor (W)	Ceiling (W)	Plastic Wall (W)	Time Delay (S)
First Reflection	0.0014	0.0011	7.5239 e-004	1.7914e-004	3.000e -008
Second Reflection	3.6878 e-006	2.8581 e-006	1.9361 e-006	4.6098e-007	6.000e -008
Third Reflection	9.8873 e-010	7.6626 e-010	5.1908 e-010	1.2359e-010	1.300e -007
Fourth Reflection	4.7477 e-012	3.6795 e-012	2.4925 e-012	5.9346e-013	1.500e -007
Fifth Reflection	1.4578 e-015	1.1298 e-015	7.6537 e-016	1.8223e-016	2.300e -007
Transmitter location (10,15,3)					
Receiver location (8,8,3)					
Line of sight component = 0.0022 W					

The performance of the system was evaluated both for a big room (Table I) and standard office room (Table II) with the transmitter positioned on the ceiling and the receiver on the floor. The rooms are empty and unfurnished. Light diffusely reflected on plastic wall, plaster wall, floor and ceiling surfaces are considered. The room is equipped with five identical transmitters at different locations and all transmit the same data in phase. The system was evaluated using a Matlab program and results were validated with [2]. The transmitter emitting 1W power was deployed in empty rooms of size 15m*15m*3m and 5m*5m*3m respectively. Light reflections were considered until the fifth reflection. LOS and NLOS) components were simulated for different surfaces and summarized in Table I and Table II.

TABEL II
LIGHT REFLECTION FOR SINGLE SOURCE AT 5M*5M*3M ROOM SIZE

	Plaster Wall (W)	Floor (W)	Ceiling (W)	Plastic Wall (W)	Time Delay (S)
First Reflection	0.0159	0.0123	0.0080	0.0159	1.0000 e-008
Second Reflection	2.8547 e-004	2.2124 e-004	1.4273 e-004	2.8547 e-004	2.0000 e-008
Third Reflection	7.5382 e-007	5.8421 e-007	3.7691 e-007	7.5382 e-007	4.0000 e-008
Fourth Reflection	4.9239 e-008	3.8161 e-008	2.4620 e-008	4.9239 e-008	5.0000 e-008
Fifth Reflection	1.2567 e-010	9.7394e-011	6.2835 e-011	9.7394 e-011	8.0000 e-008
LOS component = 0.0159 W					
Transmitter location (3.5,3,3)					
Receiver location (3,2.5,3)					

IV. NATURAL LIGHT

The performance of VLC systems is impaired by shot noise from natural light, illumination light and thermal noise due to receiver load resistor at photodiode. Natural light intensity varies year round depending on factors such as time of day, meteorological conditions, communication path direction relative to the sun, receiver FOV and receiver optical system parameters e.g. photodiode sensitivity. For example, during summer periods when natural light intensity is highest ,the system may suffer catastrophic failure due to high intensity noise, especially if the detector is subject to direct incidence of natural light [8], [9], [10].

Two classes of natural light affect systems performance: direct and indirect. On average, indirect is between 10%-20% of the direct natural light [9]. Since Shot Noise is highly dependent on the sunlight level captured within the receiver FOV, and its intensity depends on whether it is direct or reflected, it is important to characterize the likelihood and the frequency of direct against indirect sunlight to better define system availability and reliability [9], [10].

According to [**1**], natural light has been categorized to five main levels,

- clear night with full moon,
- summer's day with clear sky ,
- summer's day with overcast sky,
- winter's day with clear sky
- Winter's day with overcast sky

These categories were characterised using a cosine corrected light sensor [2]; light can enter the sensor within a 180 degrees hemisphere. Natural light can thus be categorised in Table III.

TABLE III
NATURAL LIGHT LEVELS [2]

Natural light	Intensity (LUX)
Clear night, Full moon	0.3
Winter's day, Overcast sky	900-2000
Summer's day, Overcast sky	4000-20000
Winter's day , Clear Sky	Up to 9000
Summer's day , Clear Sky	Up to 100,000

According to [1], [9], no fixed conversion factors exist to convert light intensity from LUX to W/m^2. For the analysis here, LUX is converted to watts/m^2 for day light by multiplying with 0.00402, only appropriate for the visible light band of interest [2].

V. SYSTEM PERFORMANCE

Signal to Noise Ratio (SNR) was calculated for each natural light category listed in Table III. Monte Carlo simulation together with a Matlab routine were used to model the system, simulate and evaluate the average SNR for each light category. The analysis was carried out for a 100 Kbit/s data rate and 0.54 $A/_W$ photodiode responsivity.

Clear Night Full Moon

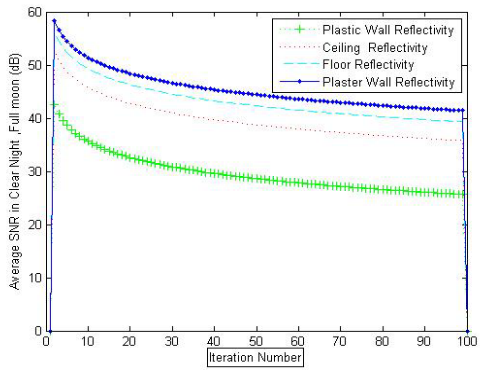

Fig. 2 Average SNR in clear night, full moon

Fig. 2 shows that average SNR for plaster wall, ceiling, floor and plastic surfaces; the effect of natural light was weak since the SNR is relatively high. The Average SNR for plastic wall (lowest surface reflectivity) was ~30 dB; ~46 dB for plaster walls (highest surface reflectivity); ~42dB and ~45dB for ceiling and floor respectively. The system can provide a 10^{-11} BER in this case of natural light and data rate.

Winter's Day, Overcast Sky

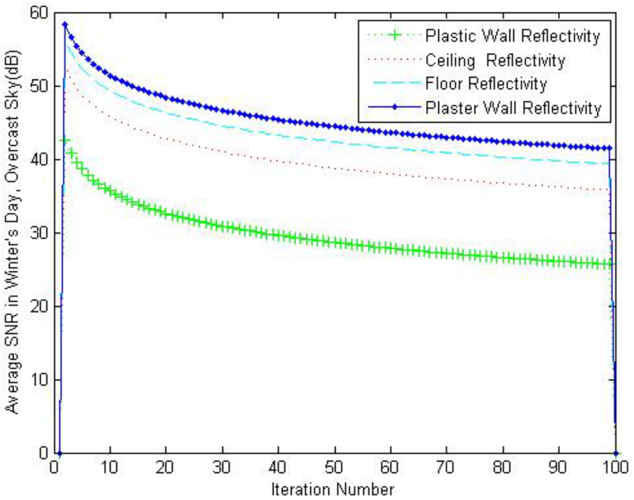

Fig. 3 Average SNR in winter's day overcast sky

For this case, the average SNR for plastic walls reduces to ~28dB compared (Fig. 3) to the clear night full moon case. For plaster walls, a slight decrease to ~44dB is observed; for ceiling and floor surfaces it decreased to ~39dB and ~42dB respectively.

Winter Day Clear Sky

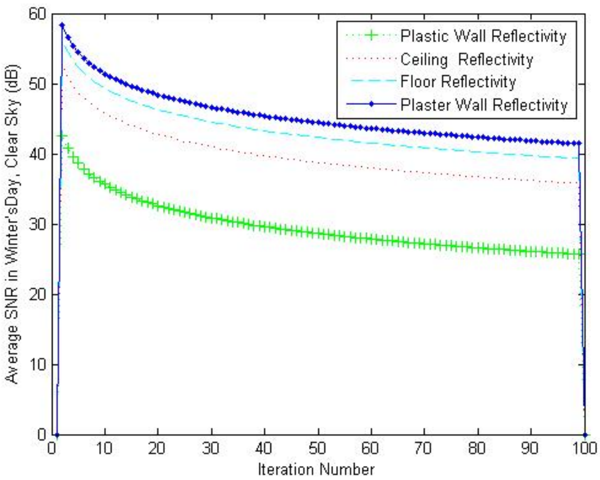

Fig. 4 Average SNR in winter's day, clear sky

A clear sky condition further degrades the SNR. The SNR reduces to ~27dB for plastic walls and ~43dB for plaster walls. The SNR for floor and ceiling surfaces was lower, but the required level of BER was still attainable.

Summer's Day, Overcast Sky

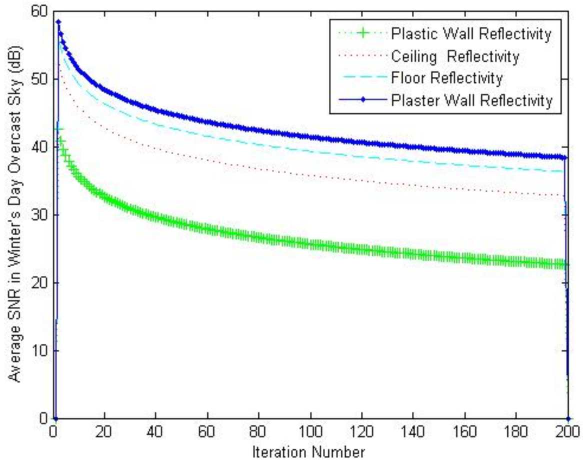

Fig. 5 Average SNR in summer's day, overcast sky

In the summer when the sunlight intensity is highest - in the 4000 to 20000 LUX range - the shot noise increases reducing the SNR from ~40 dB to ~24dB for plastic walls (Fig.4) compared to clear night full moon case. Moreover the SNR decreases to ~35dB, ~39dB and ~41 dB for ceiling, floor and plaster wall surfaces respectively. A slight degradation was evident on comparison of winter to summer for the overcast sky cases.

Summer's Day, Clear Sky

During a sunny day and the sky is clear, sunlight intensity may reach up to 100,000 LUX. As a consequence, the SNR decreases to ~20dB for plastic walls. In the case of plaster walls, the SNR did not degrade by the same percentage due to high reflectivity, being ~40dB (Fig.6). Moreover the SNR decreases to ~34dB and ~37 dB for ceiling and floor surfaces respectively.

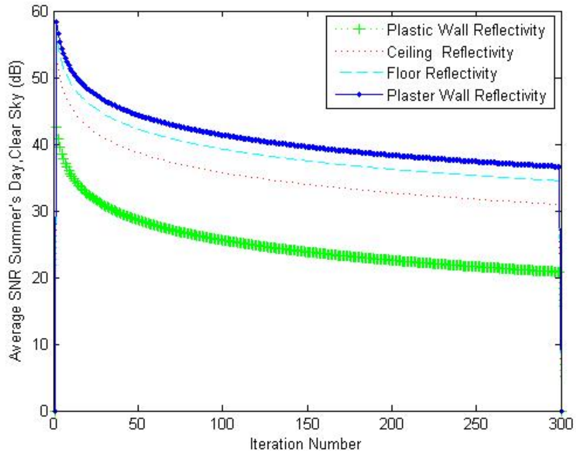

Fig. 6 Average SNR in summer's day, clear Sky

VI. Conclusion

The impact of natural light on VLC system performance was evaluated for a number of conditions; clear night-full moon, summer's day- clear sky, winter's day - clear sky , summer's day -overcast sky and winter's day -overcast sky (Table IV) .The evaluation also considered a range of surfaces; plaster walls provided the best SNR performance when compared to floor, plastic walls and ceiling surfaces NLOS component decreases for every reflection considered, especially in relatively spacious environments (15m*15m*3m). The fourth and fifth reflections can be neglected due to the negligible effect on system performance. As expected, the lowest SNR (and BER) occurred for summer's day, clear sky since the natural light intensity reaches its maximum.

TABLE IV
Summary of SNR Over the Main Five Categories

Natural light level/ SNR (dB)	Plastic wall	Plaster wall	Floor	Ceiling
Clear night full moon	30	46	45	42
Summer's day with clear sky	20	40	37	34
Summer's day with overcast sky	24	41	39	35
Winter's day with clear sky	27	43	42	40
Winter's day with overcast sky	28	44	42	39

In summary, the availability of VLC systems is a strong function of the level of natural sunlight and indeed may be compromised under high intensity scenarios such as encountered during the summer.

References

[1] Light measurement guidance notes, www.skyeninstruments.com, 1-2-2012, 19:45.
[2] Kwonhyung Lee; Hyuncheol Park; Barry, J.R., "Indoor Channel Characteristics for Visible Light Communications," Communications Letters, IEEE, vol.15, no.2, pp.217-219, February 2011.
[3] Gfeller, F.R.; Bapst, U., "Wireless in-house data communication via diffuse infrared radiation," Proceedings of the IEEE, vol.67, no.11, pp. 1474- 1486, Nov. 1979.
[4] Lubin Zeng; Hoa Le Minh; O'Brien, D.; Faulkner, G.; Kyungwoo Lee; Daekwang Jung; YunJe Oh; , "Equalisation for high-speed Visible Light Communications using white-LEDs," Communication Systems, Networks and Digital Signal Processing, 2008. CNSDSP 2008. 6th International Symposium, vol., no., pp.170-173, 25-25 July 2008.
[5] Barry, J.R.; Kahn, J.M.; Krause, W.J.; Lee, E.A.; Messerschmitt, D.G.; , "Simulation of multipath impulse response for indoor wireless optical channels," Selected Areas in Communications, IEEE Journal on , vol.11, no.3, pp.367-379, Apr 1993.
[6] J Komine, T.; Nakagawa, M.; "Fundamental analysis for visible-light communication system using LED lights," Consumer Electronics, IEEE Transactions, vol.50, no.1, pp. 100- 107, Feb 2004.
[7] Kahn, J.M.; Barry, J.R.; "Wireless infrared communications," Proceedings of the IEEE, vol.85, no.2, pp.265-298, Feb 1997.
[8] Ramirez, R.; Idrus, S. and Johor, s.; Optical wireless communications IR for wireless connectivity, CRC press, Taylor & Francis, 2008.
[9] Moreira,A.;Valadas,r.; and Duarte ,O.; Optical interference produced by artificial light, Science Publishers, Portugal, 1997.
[10] Sidorovich et.al. Solar background effects in wireless optical communications, proceeding of SPIE, Vol.4873, 2002.
[11] R. Billinton and W. Y. Li," Reliability Assessment of Electrical Power Systems Using Monte Carlo Method", Plenum Press, New York, 1994.